

# Polarization diffraction grating produced by femtosecond laser nanostructuring in glass

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We demonstrate a polarization-sensitive diffractive optical element by femtosecond laser direct writing of light-induced self-assembled nano-gratings in bulk silica glass. Manipulation of the induced form birefringence is achieved by controlling the writing parameters, in particular, the polarization azimuth of the writing beam. The performance of the diffraction-based circular-polarization beam splitter agrees with the theoretical prediction. The method allows extending the operation of space-variant subwavelength gratings of beam polarization converters to the visible range. © 2010 Optical Society of America

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Recently femtosecond laser material processing has attracted considerable interest due to the wide range of applications, from micromachining to nanofabrication capable of resolution below 100 nm [1]. When a femtosecond laser beam is focused into silica glass, at a certain intensity level anisotropic modification is created [2–4]. The origin of the anisotropy is attributed to form birefringence due to spontaneous formation of subwavelength periodic structures oriented perpendicular to the writing beam polarization in the focal volume [5–7]. Such subwavelength structures behave as a negative uniaxial crystal [8], with the slow and fast optical axes aligned, respectively, parallel and perpendicular to the grating corrugation.

Several types of devices employing self-assembled nano-gratings have already been demonstrated: birefringent Fresnel zone plates [9], nano-fluidic channels, rewritable optical memory [10,11], and computer-generated holograms [12]. However, as far as we know, the possibility of harnessing self-assembled nano-gratings to create polarization diffractive optical elements has not yet been explored. On the other hand, there is increasing interest in such devices [13] due to variety of prospective functions, such as beam splitters [14,15], azimuthal and radial polarization state converters [16], and coronagraphs [17]. Currently used methods of achieving polarization control include spatial light modulators [15] and photolithographically produced subwavelength gratings [14]. Despite their flexibility, spatial light modulators are expensive, bulky, and operational only at moderate laser powers. Photolithography procedures are limited by resolution. Here we demonstrate the potential of femtosecond laser nanostructuring to produce structures with space-variant birefringence designed for operation in the visible range directly in the optical material.

A regeneratively amplified, mode-locked Yb:KGW (Yb-doped potassium gadolinium tungstate)-based femtosecond laser system (Pharos, Light Conversion Ltd.) operating at 1030 nm and delivering pulses of 270 fs at 200 kHz repetition rate was utilized in the experiments. The pulse energy was set to 0.5  $\mu$ J, where nano-gratings are known to be formed. The

light beam was focused via a 100 $\times$  (N.A. 0.7) Mitutoyo objective into a fused-silica plate 70  $\mu$ m below the surface. The sample was mounted onto a computer-controlled XYZ Aerotech translation stage. The laser beam polarization azimuth was manipulated by an achromatic half-wave plate mounted onto a motorized rotation stage.

The polarization diffraction grating (PDG) could be produced by periodic varying of the birefringence slow axis azimuth [14,15]. When a beam with uniform polarization propagates through the grating, the polarization and phase of the transmitted light field become periodic in space. This is different from an ordinary diffraction grating, which modulates only phase and amplitude.

In our experiment a PDG of dimensions 1 mm  $\times$  1 mm (Fig. 1) was produced by successively writing 1-mm-long lines separated by 2  $\mu$ m at a speed of 200  $\mu$ m/s. Before writing a new line, the half-wave plate was rotated by a certain angle resulting in the final PDG period of 125  $\mu$ m. The total processing time was about 1 h, which can be significantly reduced by optimizing manufacturing parameters.

When the laser beam polarization was at  $\sim 45^\circ$  to the writing direction, the imprinted lines were asymmetric, with one edge less defined than the other (Fig. 2). Reversing scanning direction also reversed this feature and led to inhomogeneity of the written structures, thus degrading the quality of the produced diffractive element. We relate this effect to light interaction with the material at the written lines' boundaries, which is of a nature different from previously reported "quill" and non-reciprocal writing [18,19]. The PDG was written by scanning only in one direction, which avoided this problem.

With a quantitative birefringence microscope (Abrio CRi) we confirmed successful realization of the desired slow axis variation and measured the induced retardance of about 90 nm (Fig. 1) for 515 nm wavelength. The diffraction properties of the PDG were characterized with Nd:YAG (532 nm) (Fig. 3) and He-Ne (633 nm) (Fig. 4) continuous-wave lasers. The different diffraction patterns with respect to the

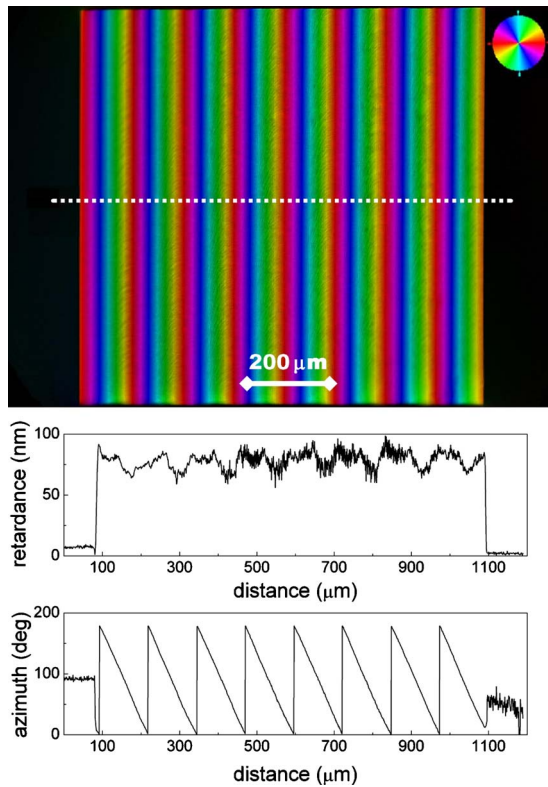


Fig. 1. (Color online) (Top) quantitative birefringence microscopy image of a polarization diffraction grating. Pseudocolor indicates azimuth of the slow axis. Retardance (middle) and azimuth (bottom) profiles taken along the white dotted line.

incident polarization state can be seen clearly in Fig. 3. The fluctuations of induced birefringence (Fig. 1) did not affect the observed diffraction. The linearly polarized beam was diffracted into 0,  $-1$ , and  $+1$  orders with the ratio of the amplitudes being 0.12:1:0.11 (Fig. 4) for measurements taken at 633 nm. For a left-hand circular polarization only 0 and  $+1$  diffraction orders were present (amplitude ratio 0.21:1:0), while right-hand circular polarization resulted in 0 and  $-1$  diffraction orders (amplitude ratio 0:1:0.18). This proved that the observed diffraction was caused by the space-variant birefringence of the written structure. The retardance at 633 nm of

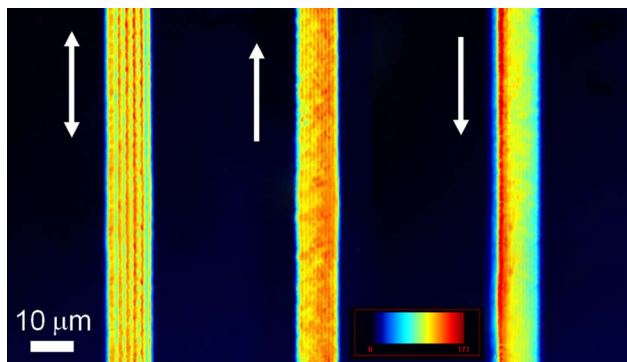


Fig. 2. (Color online) Retardance dependence of written lines when polarization azimuth is at  $45^\circ$  to the writing direction. Structures are produced by lines separated by  $1\ \mu\text{m}$ ; white arrows indicate sample translation direction.

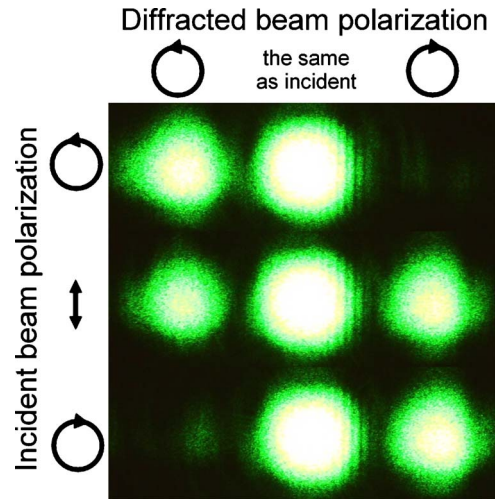


Fig. 3. (Color online) Far-field diffraction images for linear and circular incident polarizations. Incident polarization state is indicated on the left side.

about 89 nm was estimated from the amplitude ratios, which correlates well with independent birefringence measurements (Fig. 1). An extra diffraction, arising from the periodic nature of the line scanning, appeared at larger angles. It was polarization insensitive and account for 4% of the incident light.

If an extra retardance is added by placing a liquid crystal compensator in the light pass of the microscope, the birefringent zone appears colored under crossed polarizers (Fig. 5, left). This coloration is well known in polarization microscopy and occurs when the optical path length difference due to birefringence is of the order of wavelength. The ability to control retardance to submicrometer resolution and print colored graphics inside glass can be applied for security marking (Fig. 5, right).

Theoretical analysis performed using Jones matrix formalism reveals that the intensity distribution between maxima depends on the retardance value [14,20]. The diffraction efficiency can be evaluated by calculating the amplitudes of diffraction orders:

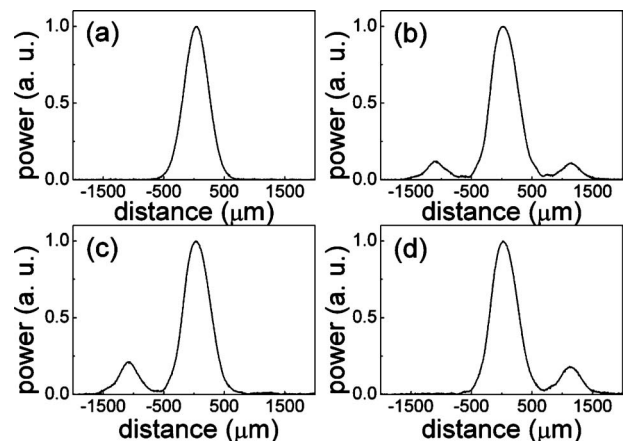


Fig. 4. Diffraction profiles measured for a He-Ne laser with a beam profile meter: (a) incident beam profile, (b) diffraction pattern for linear polarization, (c), (d) diffraction patterns for left- and right-handed circular polarizations, respectively.

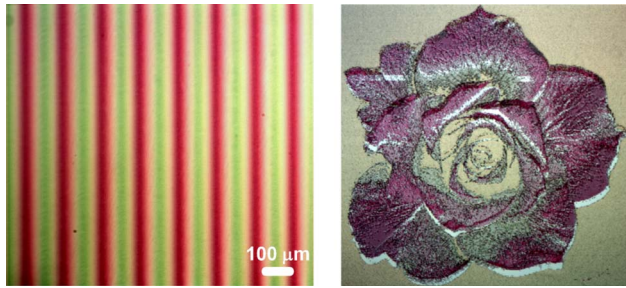


Fig. 5. (Color online) (Left) Coloration of birefringent structure in crossed polarizers when an additional constant retarder is added. (Right) Birefringent rose printed in silica glass using ultrashort light pulses. (Colors are enhanced.)

$$\eta_0 = \left| \frac{1}{2}(t_x + t_y e^{i\phi}) \right|^2,$$

$$\eta_{-1,1} = \left| \frac{1}{2}(t_x - t_y e^{i\phi}) \langle \mathbf{E}_{in} | \mathbf{RH}, \mathbf{LH} \rangle \right|^2, \quad (1)$$

where  $\eta_0$ ,  $\eta_1$ , and  $\eta_{-1}$  are amplitudes for 0, 1, and -1 diffraction orders, respectively, while  $t_x$  and  $t_y$  are transmission coefficients for polarization parallel and perpendicular to the subwavelength grating grooves, respectively. The phase shift due to retardance is denoted as  $\phi$  and expressed as  $\phi = 2\pi\Delta\Lambda/\lambda_0$ , where  $\Delta\Lambda$  is the retardance and  $\lambda_0$  is the wavelength of the incident light in vacuum. Dirac brackets denote polarization states:  $|\mathbf{E}_{in}\rangle$ ,  $|\mathbf{LH}\rangle$ ,  $|\mathbf{RH}\rangle$  are Jones matrices for incident light and left-hand and right-hand polarizations. Assuming that  $t_x = t_y = 1$  diffraction orders are expressed as

$$\eta_0 = \frac{1}{2}(1 + \cos \phi),$$

$$\eta_{-1,1} = \frac{1}{2}(1 - \cos \phi) \langle \mathbf{E}_{in} | \mathbf{RH}, \mathbf{LH} \rangle^2, \quad (2)$$

we can see from Eq. (2) that increasing the retardance leads to the energy transfer from the 0 order to adjacent ones. When the phase shift is equal to  $\pi$  the 0 order, which preserves the incident polarization state, completely disappears. The -1 and +1 orders are right- and left-hand circularly polarized. In our case (assuming retardance value of  $\sim 90$  nm), about 20% of incident light is diffracted into -1 and +1 orders.

We also carried out a series of experiments to achieve higher retardance in a single scan. Increasing the laser energy resulted in slightly stronger birefringence of about 100 nm at  $0.75 \mu\text{J}$ . The quality of the induced nano-grating deteriorated above this energy. The retardance up to 150 nm (at pulse energy

of  $0.75 \mu\text{J}$ ) was achieved by focusing the laser beam deeper into the sample due to the extended Rayleigh range caused by spherical aberration. Alternatively, higher retardance can be produced using an objective with lower numerical aperture or stacking several birefringent layers.

In summary, by exploiting the ability of femtosecond lasers to create anisotropic modification inside silica glass, we fabricated a polarization diffraction grating operating in the visible spectrum range. This approach is advantageous over current fabrication techniques for polarization diffractive optical elements by virtue of being a single-step process and enabling complex birefringence-variant three-dimensional geometries.

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